LABORATORY III
ENERGY AND CAPACITORS

All biological systems rely on the ability to store and transfer electrical energy. One feature that many of these systems have in common is a structure that behaves like a capacitor, the simplest device that stores electrical energy. By studying the way capacitors store and transfer energy, you can gain insight into the way many biological systems store and transfer energy. In this laboratory you will investigate the storage and transfer of energy in capacitors.

The problems in this lab involve transferring stored electrical energy as work or as light.

OBJECTIVES:

After successfully completing this laboratory, you should be able to:

- Apply the concept of conservation of energy to solve problems involving electrical phenomena.
- Describe the energy stored in a capacitor based on how it is connected to other capacitors and to sources of potential differences.
- Describe the rate at which a capacitor loses or gains energy based upon the system in which it is involved.

PREPARATION:

Read Serway & Jewett: Chapter 20, sections 7, 8, and 9 and Chapter 6 section 5.

Before coming to lab you should be able to:

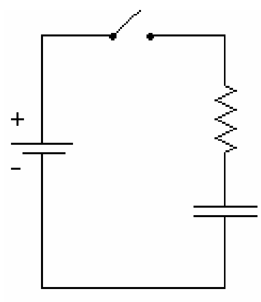
- Calculate the energy stored in a capacitor as a function of its capacitance and its voltage.
- Calculate the energy of an object given its speed and mass.
- Solve the rate equation, $\frac{dN(t)}{dt} = A \cdot N(t)$, and understand all quantities involved.

PROBLEM #1:
CHARGING A CAPACITOR

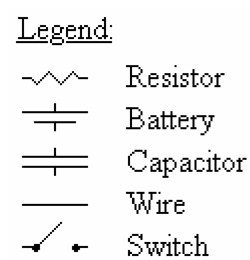
One summer you volunteer at a summer biology camp for high school students. You plan to demonstrate the effect of lightning on the creation of organic substances. To imitate the lightning, you will use a capacitor to be discharged in the atmosphere. Each time the capacitor is discharged, it must be recharged for the next demonstration. To save time, you want to charge the capacitor as fast as possible. However, you are not sure whether the resistance in series with the capacitor should be small or large to achieve quick recharging of the capacitor. To find the answer, you model the circuit with a capacitor, a resistor, and a battery in series. In a circuit consisting of a battery, a capacitor (initially uncharged), and a resistor, all in series, how does the time taken for the current in the circuit to fall to 1/8 of its initial value depend upon the resistance of the resistor?

EQUIPMENT

Build the circuit shown below using wires, resistors, capacitors, and batteries. Use the accompanying legend to help you build the circuits. You will also have a stopwatch, a light bulb, and a digital multimeter (DMM).



Circuit



PREDICTIONS

How does the time taken for the current in the circuit to fall to 1/8 of its initial value depend upon the resistance of the resistor?

Sketch a graph of the time taken for the current to fall to 1/8 of its initial value against the resistance of the resistor.

WARM-UP

Read Serway & Jewett: sections 21.1, 21.2, 21.8, 21.9.

1. Draw a circuit diagram, similar to the one shown above. Decide on the properties of each of the elements of the circuit that are relevant to the problem, and label them on your diagram. Label the potential difference across each of the elements of the circuit. Label the current in the circuit and the charge on the capacitor.

2. Recall from Kirchhoff's loop rule that the sum of potential differences across each element around any closed circuit loop is zero. Write an equation relating the potential difference across each of the elements of the circuit.

3. What is the relationship between the potential difference across the capacitor plates and the charge stored on its plates? What is the relationship between the current through the resistor and the voltage across it? Are these equations always true, or only for specific times?

4. Use these relationships to rewrite your Kirchhoff loop equation in terms of the voltage of the battery, the capacitance of the capacitor, the resistance of the resistor, the current through the circuit, and the charge stored on the capacitor.

5. Explain how each of the quantities labeled on your diagram changes with time. What is the voltage across each of the elements of the circuit (a) at the instant the circuit is closed, (b) when the capacitor is fully charged? What is the current in the circuit at these two times? What is the charge on the capacitor at these two times?

6. Write an equation relating the rate that charge accumulates on the capacitor to the current through the circuit. To do this, determine how the rate at which the charge on the capacitor is changing relates to the rate at which charge comes from the battery. Then, determine how the rate at which charge comes from the battery relates to the current in the circuit.

7. The unknown quantity in your loop equation is the current in the circuit and the charge on the capacitor. You need to eliminate the charge on the capacitor from your equations to obtain an equation for the current in the circuit in terms of the known quantities. You may find it helpful to differentiate both sides of the equation with respect to time and use the relationship from step 6 to eliminate the charge.

8. Solve the equation from the previous step for current by using one of the following techniques: (a) Guess the current as a function of time, which satisfies the equation, and check it; (b) Get all the terms involving current on one side of the equation and time on the other side and solve. Solving the equation may require an integral.

9. Complete your solution by determining any arbitrary constants in your solution, using the initial value of the current obtained above (what is the current when t=0?)

10. Using your equation for the current, write an expression for the time taken for the current to fall to half its initial value. Now find an expression for the time taken for the current in the circuit to halve again, and so on. How does the time for the current to halve change as the time since the circuit was closed increases?

11. How does the time it takes for the current to drop to 1/8 of its original value compare to the time it takes for the current to drop to 1/2 of its original value? How does that time depend on the resistance in the circuit? Sketch a graph of that time vs. the resistance.

EXPLORATION

WARNING: A charged capacitor can discharge quickly producing a painful spark. **Do not** handle the capacitors by their electrical terminals or connected wires by their metal ends. **Always discharge a capacitor when you are finished using it.** To discharge a capacitor, use an insulated wire to briefly connect one of the terminals to the other.

Note: Make sure the + terminal of the battery is connected to the + terminal of the capacitor! Like some biological capacitors, these capacitors are only designed to charge one way. If you connect the capacitors up the wrong way, the capacitance will change in an unpredictable manner.

Examine each element of the circuit **before** you build it. How do you know if the battery is "good"? Is the capacitor charged? Carefully connect the two terminals of the capacitor to ensure it is uncharged. How can you determine the resistance of the resistor? Is there a way to confirm it?

After you are convinced that all of the circuit elements are working and that the capacitor is uncharged, build the Circuit **with a light bulb in place of the resistor**, but leave the circuit open.

Close the circuit and observe how the brightness of the bulb changes with time. What can you infer about the way the current in the circuit changes with time? From what you know about a battery, how does the potential difference (voltage) across the battery change over time? Check this using the DMM set for potential difference (Volts). From your observations of the brightness of the bulb, how does the potential difference across the bulb change over time? Check this using the DMM. What can you infer about the change of voltage across the capacitor over time? Can you check with a DMM? Use the concept of potential difference to explain what you observe.

Now, discharge the capacitor, and reconnect the DMM in such a way that it measures the current in the circuit. Close the circuit and observe how the current changes with time? Is it as you expected? How long does it take for the current to fall to zero?

Replace the light bulb with a resistor. Qualitatively, how will changing the resistance of the resistor and the capacitance of the capacitor affect the way the current in the circuit changes with time? How can you test this experimentally?

Build the circuit, including a DMM in the circuit to measure the current. Close the circuit and observe how long it takes for the current in the circuit to halve. How does changing the capacitance of the capacitor or the resistance of the resistor affect this time? Choose a value of the capacitance of the capacitor and a range of resistances that allow you to most effectively construct a graph to test your prediction.

Complete your measurement plan.

MEASUREMENT

Measure the time taken for the current in the circuit to drop to 1/8 of its initial value for different resistance of the resistor. Do this at least twice for each resistor for averaging.

ANALYSIS

Using the measured values of the capacitance of the capacitor, the resistances of the resistors, and the voltage of the battery, construct a graph of your prediction of the time it takes the current to drop to 1/8 of its initial value vs. resistance. Using your data, construct a graph of the measured times versus resistance.

CONCLUSION

How does the time taken for the current in the circuit to drop to 1/8 of its initial value depend upon the resistance of the resistor?

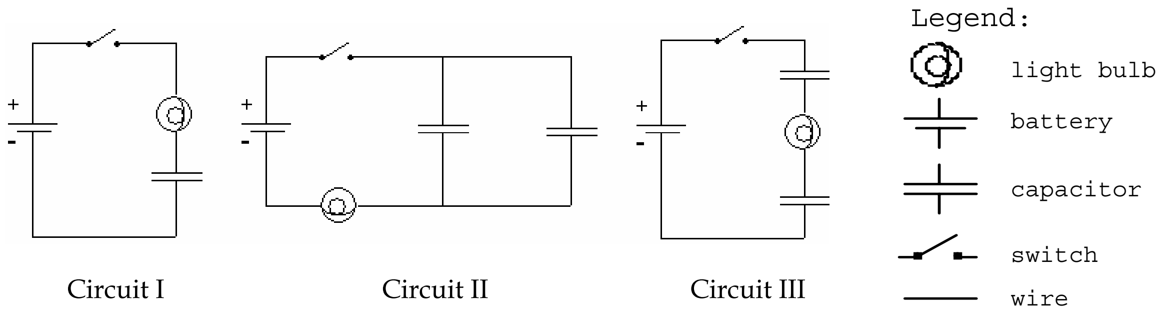
Compare your prediction result with your measurement result. Explain any differences.

PROBLEM #2:
CONNECTION OF TWO CAPACITORS

You are working in a research group of the University, which is studying the effect of sudden currents on protein suspensions. The method used in the research is to charge a capacitor and discharge it to provide a large current. One day, you need to increase the capacitance of the capacitor to get larger discharging current. However, no larger capacitor is available. Fortunately, you have another capacitor with smaller capacitance than the original. You wish to use both capacitors at the same time, but you are not sure how to connect the two capacitors together to achieve maximum capacitance. To model the situation, you set up three kinds of circuits with the capacitors. For each, you will investigate how long it takes for the bulb to dim after the circuit is closed. You think that the longer the time, the larger the capacitance. How does the capacitance of two capacitors in parallel compare to that of two capacitors in series?

EQUIPMENT

Build the circuits shown below out of wires, resistors, capacitors with equal capacitance, and batteries. You will also have a stopwatch and a digital multimeter (DMM).



Circuit I　　Circuit II　　Circuit III

Note: Some of the light bulbs in the lab may be of different kinds and have different resistances. To find identical light bulbs look for markings and check to see that the color of the plastic bead separating the filament wires is the same.

PREDICTION

Graph the current in each of Circuits I, II, and III as functions of time, assuming each capacitor has the same capacitance. Rank the total time it takes for the bulbs in Circuits I, II, and III to turn off from shortest to longest.

WARM-UP

Read Serway & Jewett: sections 20.7, 20.8, 21.1, 21.2, 21.8, 21.9.

1. For each of the circuits, draw a circuit diagram. Decide on the properties of each of the elements of the circuit that are relevant to the problem, and label them on your diagram. Label the potential difference across each of the elements of the circuit. Label the current in the circuit and the charge on each capacitor. What about the two capacitors of Circuit III? When will the bulb go out?

2. Recall from Kirchhoff's loop rule that the sum of potential differences across each element around any closed circuit loop is zero. Write an equation relating the potential difference across each of the elements of Circuit II. Do the same for two closed circuit loops in Circuit III. What is the relationship between the charges on the two capacitors in Circuit II? What is the relationship between the charges on the two capacitors in Circuit III?

3. What is the relationship between the potential difference across the plates of each capacitor and the charge stored on its plates? What is the relationship between the current through the bulb and the voltage across it? Are these equations always true, or only for specific times?

4. Use these relationships to rewrite your Kirchhoff loop equations in terms of the voltage of the battery, the capacitance of each of the capacitors, the resistance of the bulb, the current through the circuit, and the charge stored on each of the capacitors.

5. Explain how each of the quantities labeled on your diagram changes with time. What is the voltage across each of the elements of the circuit (a) at the instant the circuit is closed, (b) when the capacitor is fully charged? What is the current in the circuit between these two times? What is the charge on each of the capacitors between these two times?

6. Write an equation relating the rate that charge accumulates on each of the capacitors to the current through the circuit. To do this, determine how the rate at which the charge on each of the capacitors is changing relates to the rate at which charge comes from the battery. Then, determine how the rate at which charge comes from the battery relates to the current in the circuit.

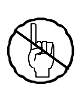
7. The unknown quantities in your loop equations are the current in the circuit and the charge on each of the capacitors. You need to eliminate the charge on each of the capacitors from your equations to obtain an equation for the current in the circuit in terms of the known quantities. You may find it helpful to differentiate both sides of each equation with respect to time and use the relationship from step 6 to eliminate the charge.

8. Solve the equation from the previous step for current by using one of the following techniques: (a) Guess the current as a function of time, which satisfies the equation, and check it; (b) Get all the terms involving current on one side of the equation and time on the other side and solve. Solving the equation may require an integral.

9. Complete your solution by determining any arbitrary constants in your solution, using the initial value of the current obtained above (what is the current when $t=0$?).

10. Complete the above steps for the all of the circuits. How does the equation for current as a function of time compare for Circuits I, II, and III? Sketch a graph of current versus time for all three circuits (plot them on the same graph). In which circuit do you expect the bulb to go out first?

EXPLORATION



WARNING: A charged capacitor can discharge quickly producing a painful spark. **Do not** handle the capacitors by their electrical terminals or connected wires by their metal ends. **Always discharge a capacitor when you are finished using it.** To discharge a capacitor, use an insulated wire to briefly connect one of the terminals to the other.

Note: Make sure the + terminal of the battery is connected to the + terminal of the capacitor! Like some biological capacitors, these capacitors are only designed to charge one way. If you connect the capacitors up the wrong way, the capacitance will change in an unpredictable manner.

Review your exploration from the previous problem. Examine each element of the circuit **before** you build it. How do you know if the battery is "good"? Are the capacitors charged? Carefully connect the two terminals of each capacitor to ensure it is uncharged. Make sure your two capacitors have the same capacitance. Begin your observations by using bulbs instead of resistors.

Build Circuit II, but do not close the circuit. Do you think the bulb will light when the circuit is closed? Record your reasoning. Close the circuit. Record your observations and explain what you saw using conservation of charge and the concept of potential difference

Build Circuit III, but do not close the circuit. Do you think the bulb will light when the circuit is closed? Record your reasoning in your journal. Close the circuit. Record your observations and explain what you saw using conservation of charge and the concept of potential difference. Does the order that you connect the two capacitors and the bulb in the circuit matter? Try following one capacitor with the other capacitor and then the bulb.

Now, replace the light bulbs in your circuits with resistors. How can you determine the resistance of the resistor? Is there a way to confirm it?

Connect a DMM in each of the circuits and observe how the current changes with time. For each circuit, decide how many measurements you will need to make in order to make a graph of current against time, and what time interval between measurements you will choose. Complete your measurement plan.

MEASUREMENT

Measure the current in each circuit for as many different times as you deem necessary. Make your measurements using resistors, not bulbs. What are the uncertainties in each of these measurements?

ANALYSIS

Draw graphs of the measured values of the current as a function of time for each of the circuits I, II, and III.

CONCLUSION

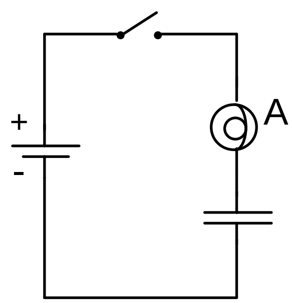
How well do your graphs drawn from your data compare to those drawn from your prediction? Explain any difference.

PROBLEM #3:
CAPACITORS I

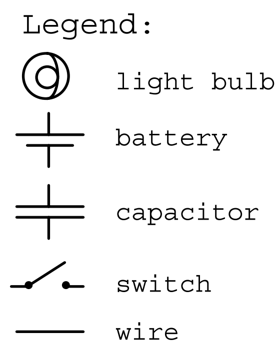
You and a friend are discussing how ion concentrations on either side of a cell membrane change with time. In particular you want to investigate how ions (say Na+) migrate and how voltage across the membrane builds up over time. To clarify this, you model the cell membrane very crudely as a capacitor in series with a light bulb and battery. A capacitor can be thought of as a device used to hold separated charges (similar to the cell membrane).Your friend claims that when the switch is closed the capacitor charges up and the bulb gets brighter and brighter until the brightness levels off. The bulb then stays on until the switch is opened. Do you agree? In a circuit consisting of a battery, a bulb, and a capacitor, determine how the brightness of the bulb changes with time.

EQUIPMENT

You can build the circuit shown below out of wires, bulbs, capacitors and batteries. Use the accompanying legend to help you build the circuits. You will also have a stopwatch and a digital multimeter (DMM).



Circuit I



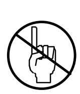
PREDICTION

Read Serway & Jewett: sections 20.7, 21.1, 21.2, 21.5, 21.9.

How do you think the brightness of the light bulb changes over time?
What is it that makes the light bulb glow? Explain.

Sketch a graph of the brightness of the bulb, as a function of time, assuming the capacitor to be initially uncharged. Is there a limit as to how much charge the capacitor can hold?

EXPLORATION



WARNING: A charged capacitor can discharge quickly producing a painful spark. **Do not** touch the metal terminals of the capacitors or the exposed metal of any wires connected to them. **Always discharge a capacitor with a wire when you are finished using it.** To discharge a capacitor, use an insulated wire to briefly connect one of the terminals to the other.

Note: Make sure the + terminal of the battery is connected to the + terminal of the capacitor! Like some biological capacitors, these capacitors are only designed to charge one way. If you connect the capacitors up the wrong way, the capacitance will change in an unpredictable manner.

Examine each element of the circuit **before** you build it. How do you know if the battery is "good"? How do you check if the capacitor is charged? How can you tell if the capacitor is completely charged? How can you be sure the capacitor is not charged?

After you are convinced that all of the circuit elements are working and that the capacitor is not charged, build the circuit but do not make the final connection yet.

Now, close the circuit and observe how the brightness of the bulb changes over time. How long does it take for any variation to cease?

From your observation of the bulb's brightness, how does the current going through the bulb change over time? You can check this using the DMM set for current (Amperes). See *Appendix D* for the use of the DMM. How does the charge on the capacitor change over the same time? Can you measure this with the DMM? Use conservation of energy to explain what you observe.

From what you know about a battery, how does the voltage across the battery change over time? Check this using the DMM set for Volts. From your observations of the brightness of the bulb, how does the voltage across the bulb change over time? Check this using the DMM. What can you infer about the change of voltage across the capacitor over time? Can you check with a DMM? Use the concept of energy to explain what you observe.

After a few moments, open the circuit. Is the capacitor charged or not? To determine if the capacitor is charged, carefully (and safely) remove the battery from the circuit and reconnect the circuit without the battery. With only the capacitor, and bulb (no battery) in the circuit, will the bulb light if you close the circuit and the capacitor is charged? Uncharged? Try it. Was the capacitor charged before you closed the circuit? Was the capacitor still charged long after the circuit was closed? Use conservation of energy to explain your results.

CONCLUSION

Was your friend right about how the brightness of the bulb changed over time?

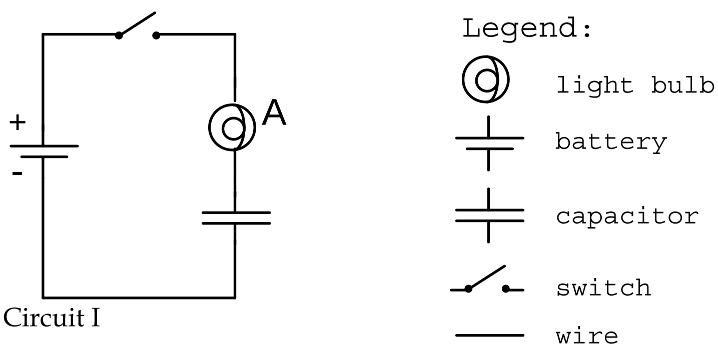
Sketch a qualitative graph of the brightness of the bulb as a function of time after you complete the circuit. How does this compare to your prediction?

PROBLEM #4:
CAPACITORS II

You and a friend are discussing how ion concentrations on either side of a cell membrane change with time. In particular you want to investigate how ions (say Na+) migrate and how voltage across the membrane builds up over time. Now you are wondering how the properties of the membrane affect the migration process. You decide to model the cell membrane, very crudely, as a capacitor in series with a light bulb and a battery. A capacitor can be thought of as a device used to hold separated charges (similar to the cell membrane). You decide to get a qualitative understanding of the rate at which a capacitor charges by using a capacitor in series with a light bulb and battery. How does the time that the light bulb is lit depend on the capacitance of the capacitor connected in series with it?

EQUIPMENT

You have the materials to build the circuit below. You will also have a stopwatch and a digital multimeter (DMM). Use the accompanying legend to help you build the circuit.



Circuit I

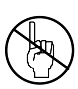
PREDICTION

Read Serway & Jewett: sections 20.7, 20.8, 21.1, 21.2, 21.5, 21.9.

From your experience, make an educated guess about how the time that the light bulb is lit depends on the capacitance of the capacitor.

Sketch a graph of the time it takes for the light bulb to turn completely off as a function of the capacitor's capacitance. Assume the capacitor is initially uncharged. Write down what you mean when you say the light bulb is completely off.

EXPLORATION



WARNING: A charged capacitor can discharge quickly producing a painful spark. **Do not** handle the capacitors by their electrical terminals or connected wires by their metal ends. **Always discharge a capacitor before you use it and after you are finished using it.**

Note: Make sure the + terminal of the battery is connected to the + terminal of the capacitor! Like some biological capacitors, these capacitors are only designed to charge one way. If you connect the capacitors up the wrong way, the capacitance will change in an unpredictable manner.

Examine each element of the circuit **before** you build it. How do you know if the battery is "good"? Be sure the capacitors are not charged.

After you are convinced that all of the circuit elements are working and that the capacitor is not charged, connect the circuit but do not close it yet.

Now, close the circuit and observe how the brightness of the bulb changes over time. How long does it take for the bulb to turn off?

From what you know about a battery, how does the voltage across the battery change over time? Check this using the DMM set for volts. From your observations of the brightness of the bulb, how does the voltage across the bulb change over time? Check this using the DMM. What can you infer about the change of voltage across the capacitor over time? Can you check with a DMM? Use the concepts of voltage and energy to explain what you observe.

Develop a measurement plan that will allow you to determine the time it takes a bulb to turn off as a function of capacitance. You will want to decide how many different capacitors you need to use, how many time measurements to take for each capacitor, and what you mean by the light bulb being 'off'.

MEASUREMENT

Use your measurement plan to record how long it takes for the light bulb to turn off for each capacitor in the circuit.

ANALYSIS

Graph the time it takes for the light bulb to turn off, as a function of capacitance, assuming the capacitor is initially uncharged.

CONCLUSION

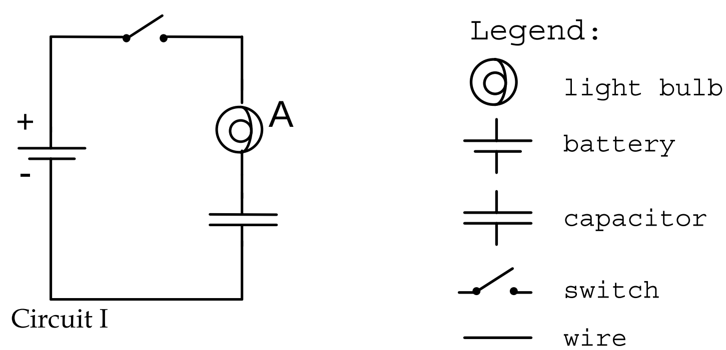
How did your measurement compare with your prediction? Using conservation of charge and conservation of energy, explain how the capacitance affects the time it takes for the bulb to turn off.

PROBLEM #5:
RATES OF ENERGY TRANSFER IN RC CIRCUITS

For a class project in biomedical electronics, you thought of developing a simple 'stun gun' for use in self-defense. The 'stun gun' has a capacitor charged to a high voltage. When a pair of electrodes at the tip of the 'gun' touch the skin of an attacker the capacitor discharges (ouch!). Being cautious, you also imagine a scenario in which the gun misses the attacker the first time, so you are concerned about how fast the gun can 'reload'. To shed light on this issue, you assembled together a circuit containing a capacitor in series with a battery and light bulb. You are interested in determining the rate and therefore the time it takes for the capacitor to charge. Can you characterize the rate at which energy enters the capacitor? What determines the time it takes for a capacitor to charge (or discharge)? In this problem you are interested in not just the total charge time but also in how energy enters the capacitor during the charging process. Determine how the energy stored in the capacitor changes as a function of time while charging.

EQUIPMENT

You have the materials to build the circuit below. You will also have a stopwatch and a digital multimeter (DMM). Use the accompanying legend to help you build the circuit.



PREDICTION

Which equation(s) will you use to determine the rate at which energy enters the capacitor?

WARM-UP

Read Serway & Jewett: sections 20.7, 20.8, 20.9, 21.1, 21.2, 21.5, 21.9.

1. In this experiment, you are looking at rates of change. Make a list of the things that are changing in the circuit while a capacitor is charging.
2. Write down appropriate rate equation(s) for properties of the circuit that change with time. Write down the meaning of each letter in the rate equation(s).
3. List the terms (letters) in the rate equation you can measure with tools in the lab. Which terms in the rate equation will you need to calculate as a result of your experiment? How many of these terms are there?

4. Explain the role of the capacitor in the rate equation.
5. Explain the role of the battery in the rate equation
6. Solve the rate equation. Are there any unknown quantities in this equation? Write them down. How about initial conditions?
7. How are the time-varying quantities, which you can measure directly and which you have written rate equation(s) for, related to the capacitor's energy? To the rate of energy input to the capacitor?
8. How is the energy stored in a capacitor related to the voltage across the capacitor terminals?

EXPLORATION

WARNING: A charged capacitor can discharge quickly producing a painful spark. **Do not** handle the capacitors by their electrical terminals or connected wires by their metal ends. **Always discharge a capacitor before you use it and after you are finished using it.** To discharge a capacitor, use an insulated wire to briefly connect one of the terminals to the other.

Note: Make sure the + terminal of the battery is connected to the + terminal of the capacitor! Like some biological capacitors, these capacitors are only designed to charge one way. If you connect the capacitors up the wrong way, the capacitance will change in an unpredictable manner.

You are interested in rates of change, so you will need to time things. Begin with the smallest capacitor available. You will need to take measurements at several times as the capacitor charges. What do you need to measure? What is the best way to coordinate data taking? You may find the "split" feature of the stopwatch to be useful. Does this capacitor charge too quickly for you to measure?

You might want to connect a resistor in series with the light bulb (or use a resistor in place of the bulb) to reduce the charging rate to something measurable. How can you measure the resistance of this combination? How much resistance does the light bulb contribute? What role does the bulb play? How are the light bulb and resistor similar? How are they different?

Try using different capacitors and resistor sizes until you find a few combinations that will allow you to get some good sets of data.

MEASUREMENT

Measure the voltage across the capacitor as a function of time. Take several measurements as the capacitor charges - you will find it easier to fit your prediction equation to a larger number of data points.

For each circuit, remove the resistor/light bulb combination and measure its resistance using the digital multimeter. Take data for a few capacitor/resistor sizes. The capacitor value written on the capacitor might not be accurate.

ANALYSIS

Using a graphing program or a spreadsheet, plot your data for voltage (and perhaps also for current) as a function of time. Plot the solution to your rate equation for the voltage. You may adjust the 'fit' parameters (e.g. the capacitance) until your measured and calculated graphs match.

From the time-evolution of the voltage across the capacitor, construct a plot of the rate at which energy is transferred to the capacitor.

CONCLUSION

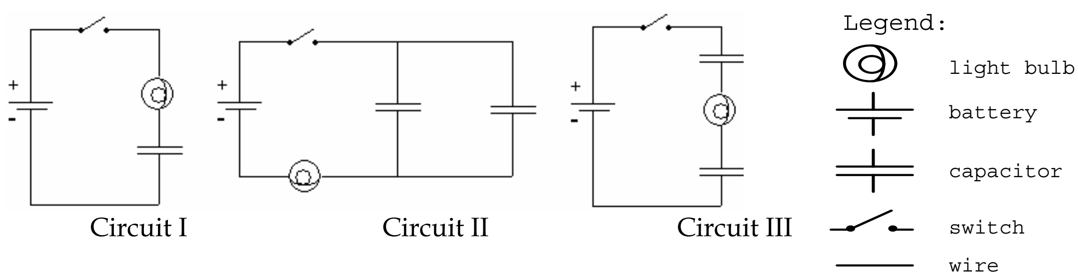
Knowing the rate at which energy enters the capacitor, what determines the time for the capacitor to charge?

PROBLEM #6:
CIRCUITS WITH TWO CAPACITORS

You have a job in a research group studying nocturnal fish. Your task is to photograph the creatures at certain intervals using a camera with an electric flash. After taking a roll of pictures you are disappointed that the flash isn't bright enough. You look in the camera and notice that the flash works by slowly charging a capacitor with a battery and then quickly releasing the stored energy through a light bulb when a photo is taken. You think that the problem with your camera may be that not enough energy is stored in the capacitor to properly light the flash bulb. You have another capacitor, of different capacitance, but aren't sure if you should connect it in series or in parallel with the original capacitor in order to store the most energy. First you calculate which of the two ways of connecting the two capacitors results in the most stored energy. Next you decide to test your calculation by seeing which one takes longest to charge through a bulb. You reason that the more the stored energy, the longer it will take to charge. Which circuit consisting of a bulb, a battery, and two capacitors takes the longest time for the bulb to dim?

EQUIPMENT

Build the circuits shown below out of wires, *identical* bulbs, two *different* capacitors, and batteries. Use the accompanying legend to help you build the circuit. You will also have a stopwatch.



Note: Some of the light bulbs in the lab may be of different kinds and have different resistances. To find identical light bulbs look for markings and check to see that the color of the plastic bead separating the filament wires is the same.

PREDICTION

Rank the total time it takes for each of the bulbs in Circuits I, II, and III to turn off (use the symbol '**=**' for "same time as"; the symbol '**>**' for "more time than"; and the symbol 'Ø' if the bulb never lights). Explain your reasoning.

WARM-UP

Read Serway & Jewett: sections 20.7, 20.8, 20.9, 21.1, 21.2, 21.5, 21.9.

1. Draw a picture of each arrangement of the capacitors, light bulb, and battery. On each picture, label the capacitance of each capacitor, remembering that you only have two capacitors, with different capacitances. Also, label the electric potential difference across each circuit element and the charge stored on each capacitor.

2. Decide on the physics principles you will use. In the case of a circuit, conservation of charge is usually useful, as is conservation of energy. What is the relationship between the total energy stored in each circuit and the energy stored on each capacitor in that circuit?

3. For each capacitor, determine an equation that relates the energy stored on its plates, the charge stored in it, and its capacitance.

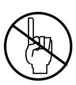
4. For each capacitor, write an equation that relates the charge on each capacitor, the potential difference across the capacitor, and the capacitance of the capacitor.

5. When the current stops flowing through the circuit, is the charge on the two capacitors in Circuit II the same? Circuit III? At that time, what is the potential difference across the bulb in each circuit? At that time, what is the relationship between the potential difference across the battery and the potential difference across each capacitor?

6. The target quantity is the energy stored in the capacitors of each circuit. To determine which is larger, you must find the energy stored in terms of common quantities such as the potential difference across the battery and the capacitance of each capacitor.

7. From step 6, you have the total energy stored in the capacitors in each circuit in terms of the potential difference across the battery and the capacitance of each capacitor. Now compare them to determine which is largest. Check your equations by making the comparison when both capacitors have the same capacitance. Does this make sense?

EXPLORATION



WARNING: A charged capacitor can discharge quickly producing a painful spark. **Do not** handle the capacitors by their electrical terminals or connected wires by their metal ends. **Always discharge a capacitor before you use it and when you are finished using it.** To discharge a capacitor, use an insulated wire to briefly connect one of the terminals to the other.

Note: Make sure the + terminal of the battery is connected to the + terminal of the capacitor! Like some biological capacitors, these capacitors are only designed to charge one way. If you connect the capacitors up the wrong way, the capacitance will change in an unpredictable manner.

Make sure all of your capacitors are uncharged before starting the exploration.

Examine each element of the circuit **before** you build it. How do you know if the battery and the bulb are "good"?

Connect Circuit I to use as a reference. Close the circuit and observe how the brightness of the bulb changes over time. How long does it take for the bulb to turn off?

Connect Circuit II using the capacitor from Circuit I along with a capacitor with a different capacitance. Do not close the circuit yet. Do you think the bulb will light when the circuit is closed? Record your reasoning in your journal. Now, close the circuit. Record your observations and explain what you saw using conservation of charge and the concept of potential difference. Does the order that you connect the two capacitors and the bulb in the circuit matter? Try following one capacitor with the other capacitor and then the bulb. Try switching the two capacitors.

After the brightness of the bulb no longer changes, what is the relationship between the potential differences across the elements of the circuit? Check this using the DMM set for potential difference (Volts). Use the concept of potential difference to explain what you observe.

Connect Circuit III using the two capacitors you used in Circuit II. Do not close the circuit yet. Do you think the bulb will light when the circuit is closed? Record your reasoning in your journal. Now, close the circuit. Record your observations and explain what you saw using conservation of charge and the concept of potential difference. Use the DMM to check the relationship between the potential differences across the elements of this circuit. Explain what you observe.

Develop a plan for measuring the time that it takes for the bulbs in Circuits I, II, and III to turn off, if they light at all.

MEASUREMENT

Use your measurement plan to record how long it takes for the light bulb to go off for each circuit. Use 0 seconds for bulbs that did not light. What are the uncertainties in these measurements?

ANALYSIS

Rank the actual time it took each bulb to turn off. Do all the bulbs initially light? Do all the bulbs go off?

CONCLUSION

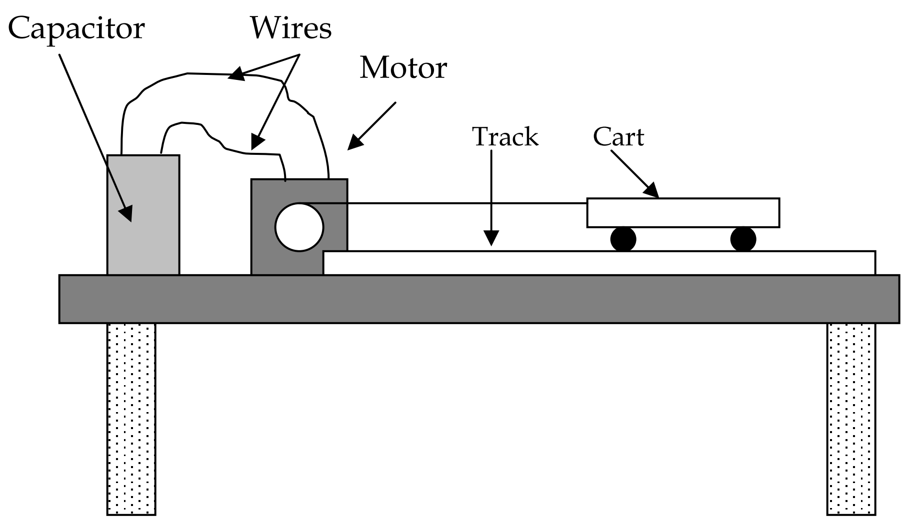
How did your initial ranking of the time it would take for the bulbs to go out compare with what actually occurred? Use conservation of charge and the concept of potential difference to explain your results.

PROBLEM #7:
EFFICIENCY OF AN ELECTRIC MOTOR

You have a job in a University research group investigating locomotion of prokaryotes such as the bacteria *Escherichia Coli*. These organisms 'swim' by rotation of rigid helical flagellum[1] like a propeller (similar to the underwater vessel in *Star Wars: Episode I*). A tiny molecular motor situated at its base drives the flagellum. The energy to drive this motor comes from hydrolysis of ATP molecules. You would like to measure the efficiency of this energy conversion process, but since the equipment for this experiment is expensive and the measurements time consuming, you would like to understand a simpler physical model first. You decide to model the energy source using a (charged) capacitor and the tiny molecular motor with a DC electric motor. A cart is pulled when the motor runs. What fraction of the energy that can be stored in a capacitor is converted into energy of the cart?

EQUIPMENT

You will have a cart that can be pulled along a track as shown. The cart will be connected with a string to a motor. You will also have several different capacitors, an aluminum track, a battery or power supply, several banana cables, a meter stick, a video camera, a computer with video analysis applications written in LabVIEW™ (VideoRECORDER and VideoTOOL), and a digital multimeter (DMM).



PREDICTION

Calculate the efficiency of the electric motor by determining the energy transferred from the capacitor and the final energy of the cart.

WARM-UP

Read Serway & Jewett: sections 6.4, 6.5, 20.7, 20.9.
Review Forces and Energy if necessary: Read Serway & Jewett: sections 6.1, 6.2, Chapter 4.

[1] R. Cotterill, *Biophysics: An Introduction*, Wiley, 2002, pp. 215-216.

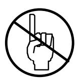
1. Draw a picture of the situation. Label all relevant distances, masses, speeds, and energies.

2. Decide on your system and the initial and final times at which you will consider your system. Write down the initial energy of your system. Write down the final energy of your system.

3. Make a list of items in the equipment that are not part of the system defined in step 2. Identify any energy transferred into or out of your system in the time interval you are using.

4. Efficiency is defined as the ratio of useful energy output divided by the energy input. Write down the energy input to the electric motor. Write down the energy output of the electric motor.

EXPLORATION



WARNING: A charged capacitor can discharge quickly producing a painful spark. **Do not** touch the metal terminals of the capacitors or the exposed metal of any wires connected to them. **Always discharge a capacitor with a wire when you are finished using it.** To discharge a capacitor, use an insulated wire to briefly connect one of the terminals to the other.

Note: Make sure you connect the + terminal of the battery to the + terminal of the capacitor! Like some biological capacitors, these capacitors are only designed to charge one way. If you connect the capacitors up the wrong way, the capacitance will change in an unpredictable manner.

Charge the capacitor by connecting it to a battery. How can you use the DMM to tell if the capacitor is fully charged? What do you mean by fully charged? Try charging it for different amounts of time. How long does it take the capacitor to fully charge?

Connect the cart to the motor with the string. Without touching the capacitor leads to anything else connect one lead to one terminal of the motor and the other lead to the other terminal of the motor. Which direction does the motor spin? Does the direction that the motor spins depend on how you connected the terminals to the motor?

How far is the cart pulled along the track? When the cart leaves the frame of the camera, is it still gaining energy? What implications does this have for your measurements? How can tell when energy is still being transferred to the cart? What happens when energy is no longer being transferred to the cart?

Write down your measurement plan.

MEASUREMENT

Use the camera to take a video of the cart as it travels a known distance. By looking at the clarity of the video picture, estimate the measurement accuracy as the speed of the cart increases.

Measure the speed of the cart after it travels a known distance. What was the speed of the cart initially? What was the energy stored in the capacitor at this time? What was the speed at the final position? What was the energy of the capacitor at the final position?

Was it necessary for the cart to be stationary initially? If the cart was not stationary, what additional information did you need to collect? How could you collect this information? Was it necessary for the capacitor to be completely discharged at the final position? If it was not, what implications does this have for your experiment? What is more important, the total energy the capacitor is able to store, or the amount of energy the capacitor transfers?

Is there a way you can visually determine that the capacitor is no longer transferring energy to the cart? What are the obvious changes to your system when energy is no longer being supplied to the cart from the capacitor?

Once you have used the analysis software on your video, which graph can you use to determine the final speed of the cart? What are the uncertainties associated with this measurement? Try to think of any possible sources of uncertainty and quantify them.

ANALYSIS

Calculate the initial energy of the cart. Calculate the final energy of the cart.

Calculate the initial energy of the capacitor. Calculate the final energy of the capacitor.

Combine the quantities you decided to be energy input and output to determine the efficiency of the electric motor. What are the implications if this number is equal to one? What if it is less than one? Greater than one?

CONCLUSION

Did your results match your predictions? Explain any differences.

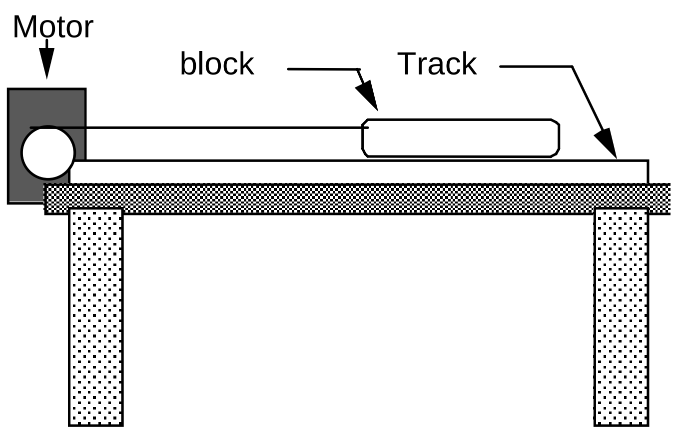
How efficient is the electric motor?

PROBLEM #8:
ELECTRICAL AND MECHANICAL ENERGY

You have a job in a University research group investigating the effect of a low gravity environment on protein synthesis. Your team is designing a small, experiment that will be carried into orbit by a satellite. As part of the experiment you need an automated pipette to add a small volume of ATP solution to a prepared protein and enzyme mixture in order to provide the energy for the protein assembly. Your team must design a lightweight power source for powering the automated pipette. You have been asked to investigate the use of capacitors. You decide to calculate how the mechanical energy transferred to a device powered by a capacitor depends on the capacitance. You will test your calculation using a laboratory model in which a capacitor provides power for a motor that drags a block of wood across a table. You calculate how far the block will move as a function of the capacitance of the capacitor, the efficiency of the system, and other properties of the block and table. You assume that you know the initial voltage on the capacitor.

EQUIPMENT

A block of wood, a track, a motor, string, several different capacitors, a battery or power supply, a meter stick, and a digital multimeter (DMM).



PREDICTION

Restate the problem. What are you trying to calculate? Express the result as both an equation and a graph.

WARM-UP

Read Serway & Jewett: sections 6.4, 6.5, 6.7, 20.7, 20.9.
Review Forces and Energy if necessary: Read Serway & Jewett: sections 6.1, 6.2, Chapter 4.

1. Draw pictures of the situation before the block moves, while the block is in motion, and after the block has come to rest. Label all relevant distances, masses, forces, and potential differences. Describe the physics principles you need to solve this problem.

2. Define the initial and final times of interest in this problem. Describe (perhaps with your diagrams) what happens to energy in the situation between those times. Indicate interactions that transform energy from one form to another or from one object to another.

3. Are there objects in the problem whose potential or kinetic energy is relevant, and that you can calculate directly in terms of quantities measurable in the lab? If so, write down expressions for their initial and final (potential or kinetic) energies.

4. Draw a force diagram for the block while it is in motion. Are there any relevant forces with magnitudes you *can* calculate, in terms of quantities you can measure in the lab? Write equations for those forces. Are there any relevant forces you *can't* calculate in terms of easily measured quantities? Indicate which forces those are.

5. What is the energy transferred to the block, in terms of the forces exerted on it and the distance it slides? Use this equation and equations from previous steps to write the amount of energy transferred from the capacitor to the block, during the entire process, as a function of the distance the block slides and properties of the block and track.

6. How would you define "efficiency" for this situation? Choose a system. Write an energy conservation equation for your system that relates the efficiency, the situation's initial conditions, and properties you can measure in the lab, to the distance the block slides.

7. Use the principal of energy conservation to write an equation for the amount of energy dissipated in this situation, in terms of measurable quantities and the efficiency. Be sure this equation is consistent with your description from step 2.

8. Sketch a graph of the distance the block slides as a function of the capacitor's capacitance. Assume constant efficiency, and that the capacitor is charged to the same potential difference for each trial. (You can check the "constant efficiency" assumption in the lab.)

EXPLORATION

WARNING: A charged capacitor can discharge quickly producing a painful spark. **Do not** handle the capacitors by their electrical terminals or handle connected wires by their metal ends. **Always discharge a capacitor with a wire when you are finished using it.** To discharge a capacitor, use an insulated wire to briefly connect one of the terminals to the other.

Note: Make sure you connect the + terminal of the battery to the + terminal of the capacitor! Like some biological capacitors, these capacitors are only designed to charge one way. If you connect the capacitors up the wrong way, the capacitance will change in an unpredictable manner.

Take the capacitor with the smallest capacitance. Give the capacitor plates a potential difference of 6 volts. Disconnect the capacitor from the battery. Explain how you can use the DMM to tell if the capacitor is fully charged or fully discharged. Explain what you mean by fully charged. Try charging for different amounts of time. Determine how long it takes the capacitor to fully charge.

Connect the block to the motor with the string. Without touching the capacitor leads to anything else connect one lead to one terminal of the motor and the other lead to the other terminal of the motor. Which direction does the motor spin? Does the direction that the motor spins depend on how you connect the motor and the capacitor? Decide the best way to connect the motor and the capacitor.

How far is the block pulled along the track? Try it for the largest capacitor as well. Does the efficiency appear to be constant? If not, can you make it more constant, or will you have to average over several trials, or is the assumption of constant efficiency simply not realized by this system? Choose a range of capacitors to give you a good range of distances (too much energy will cause the block to collide with the electric motor. If this is the case, you might try adding some mass to the block).

Write down your measurement plan.

MEASUREMENT

Measure the distance that each fully charged capacitor pulls the block. Be sure to take more than one measurement for each capacitor.

ANALYSIS

Graph the distance the block is pulled versus the capacitance of the capacitor. Show the estimated measurement uncertainty on your graph.

CONCLUSION

Did your results match your predictions? Explain any differences.

How efficient is this energy transfer? Define what you mean by efficient. How good was the assumption of constant efficiency for this situation?

You have heard that energy is always conserved. Is it appropriate to say that energy was conserved in this situation? Why or why not?

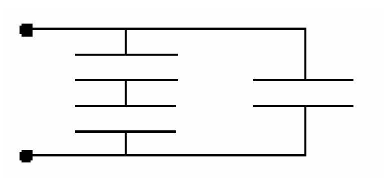
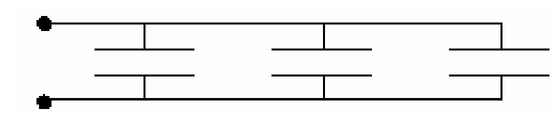
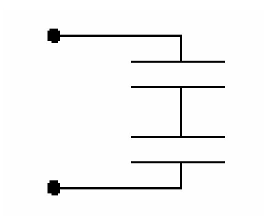
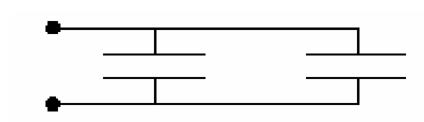
☑ CHECK YOUR UNDERSTANDING

For each of the arrangements of identical capacitors shown below:

1) Rank them in terms of the amount of time they can light a light bulb. Assume that the leads shown have been connected to a 6 Volt battery and then removed from the battery and connected to a light bulb.

2) Calculate the potential difference between the terminals of each capacitor. Assume that the leads shown have been connected to a 6 Volt battery and that the capacitance of each capacitor is 10 μF.

3) Calculate the amount of energy stored in each capacitor and the total energy stored in each arrangement of capacitors. Assume that the leads shown have been connected to a 6 Volt battery and that the capacitance of each capacitor is 10 μF.

 Arrangement 1	 Arrangement 2
 Arrangement 3	 Arrangement 4

PHYSICS 1202 LABORATORY REPORT

Laboratory III

Name and ID#: ______________________________

Date performed: ______________ Day/Time section meets: ______________________

Lab Partners' Names: ______________________________

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Problem # and Title: ______________________________

Lab Instructor's Initials: __________

Grading Checklist	Points
LABORATORY JOURNAL:	
PREDICTIONS (individual predictions and warm-up completed in journal before each lab session)	
LAB PROCEDURE (measurement plan recorded in journal, tables and graphs made in journal as data is collected, observations written in journal)	
PROBLEM REPORT:*	
ORGANIZATION (clear and readable; logical progression from problem statement through conclusions; pictures provided where necessary; correct grammar and spelling; section headings provided; physics stated correctly)	
DATA AND DATA TABLES (clear and readable; units and assigned uncertainties clearly stated)	
RESULTS (results clearly indicated; correct, logical, and well-organized calculations with uncertainties indicated; scales, labels and uncertainties on graphs; physics stated correctly)	
CONCLUSIONS (comparison to prediction & theory discussed with physics stated correctly ; possible sources of uncertainties identified; attention called to experimental problems)	
TOTAL(incorrect or missing statement of physics will result in a maximum of 60% of the total points achieved; incorrect grammar or spelling will result in a maximum of 70% of the total points achieved)	
BONUS POINTS FOR TEAMWORK (as specified by course policy)	

* An "R" in the points column means to rewrite that section only and return it to your lab instructor within two days of the return of the report to you.